GPS Accuracy versus Number of NIMA Stations

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BIOGRAPHIES

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ABSTRACT

The current GPS ground system uses five worldwide Air Force monitor stations to collect ranging data for GPS satellite clock and ephemeris estimation. Current upgrades call for the inclusion of data from six core National Imagery and Mapping Agency (NIMA) stations in ground processing as part of the Accuracy Improvement Initiative/Architecture Evolution Plan (AII/AEP). Previous analysis showed that these core NIMA stations will improve GPS accuracy by about 10% for typical broadcast users and improve filter performance (at zero-age-of-data) by as much as 40%. This paper addresses the potential benefits of adding five more NIMA stations beyond the six core stations to the GPS ground system.

The analysis shows that filter performance will improve up to 20% more due to the five additional NIMA stations. The typical broadcast user will initially gain only about 3% additional GPS accuracy improvement since broadcast accuracy is currently driven by clock prediction error. Improved earth orientation parameters, better satellite clocks, and reduced navigation message age-of-data all enhance GPS performance. The benefit of the five additional NIMA stations to the broadcast user approaches 15% if the navigation message update capability is implemented. Adding NIMA stations also improves satellite-monitoring capability that is critical for timely, robust integrity determination. Since the AII/AEP software is already designed to handle up to 20 stations, the use of five more NIMA stations requires only the addition of dedicated

communication lines, so significant accuracy and integrity improvements can be achieved at relatively low cost.

INTRODUCTION

The current GPS monitor system consists of five Air Force stations. GPS satellite tracking data from these stations is sent to the Master Control Station (MCS) at Colorado Springs. The MCS processes the ranging measurements in a Kalman filter every 15 minutes to determine satellite ephemeris and clock corrections. Periodically, about once per day for each satellite, the MCS predicts the ephemeris and clock and forms a navigation message that is sent to the satellite for transmission to the user on the GPS signal. The primary factors that affect GPS signal-in-space (SIS) user range error (URE) performance are the stability of the satellite atomic clocks, the number and distribution of monitor stations, and the frequency of navigation message uploads. GPS has demonstrated a dramatic reduction in SIS error over the past decade (Figure 1) due to the establishment of a full constellation, better clocks on Block IIR satellites, reduction of contingency upload thresholds, and enhanced Kalman filter tuning at the MCS. Current constellation SIS URE performance of about 1.5 meters root-mean-square (RMS) is four times better than the 1990 Systems Operational Requirements Document (SORD) requirement of 6 meters [1] and nearly meets the 2000 Operational Requirements Document (ORD) requirement of 1.25 meters [2].

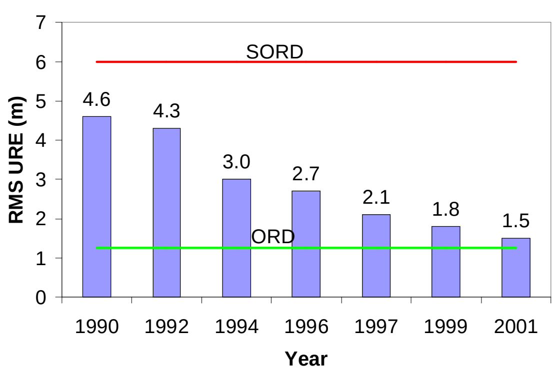

Figure 1. GPS Signal-in-Space Performance History

The Accuracy Improvement Initiative/Architecture Evolution Plan (AII/AEP) is scheduled to be implemented in the 2006 timeframe. The initiative will add data from six NIMA stations to the Kalman filter that estimates GPS satellite clock and ephemeris. The objective of this paper is to determine what additional benefits would result from adding five more NIMA stations to the network beyond the six AII/AEP stations.

The study processed real GPS tracking data from 28 satellites from August 1-15, 2002 using TRACE [3], an Aerospace-developed trajectory analysis and orbit determination program that includes a square-root information filter/smoother. Filter and broadcast performance of clock and ephemeris were evaluated against the NIMA precise clock and ephemeris for different numbers of monitor stations. Performance metrics are URE and estimated range deviation (ERD). Performance enhancements of the Wide Area GPS Enhancements (WAGE) and navigation message update (NMU) were also evaluated. Sensitivity to number of satellites, earth orientation parameter data, upload frequency, and satellite clock configuration are reported.

GROUND NETWORK VISIBILITY

The current GPS monitor system consists of five United States Air Force (USAF) stations at Hawaii, Colorado Springs, Ascension, Diego Garcia, and Kwajalein. The AII/AEP will add data from six "core" NIMA stations (USNO, Ecuador, Argentina, United Kingdom, Bahrain, and Australia) to the network (Figure 2) and implement a fully-correlated (non-partitioned) Kalman filter. The objective of this paper is to determine what additional benefits would result from adding five more NIMA stations (Alaska, Tahiti, South Africa, Korea, and New Zealand) to the network (Figure 2).

Incorporation of NIMA tracking stations into the ground network significantly improves the monitoring of the GPS satellites. Given a GPS constellation as it existed in January 2002 and assuming a five-degree elevation mask, the six core (AII) NIMA tracking stations improve monitoring performance from 97% single-station coverage to continuous, dual-station monitoring of all GPS satellites (Figure 3). The inclusion of the five additional NIMA monitor stations expands coverage from continuous, dual-station coverage to continuous, triple-station monitoring of all satellites. At higher elevation masks (e.g. 10-20 degrees), coverage is reduced, but again the five additional NIMA stations significantly improve monitoring capability. These improvements in satellite monitoring are critical for timely, robust integrity determination.

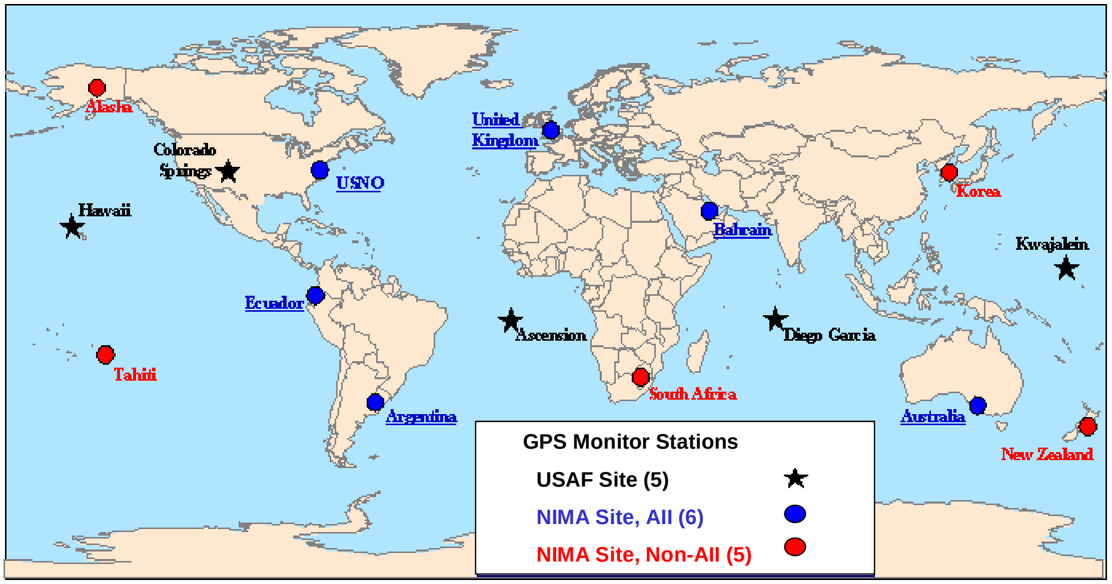

Figure 2. USAF and NIMA Tracking Stations

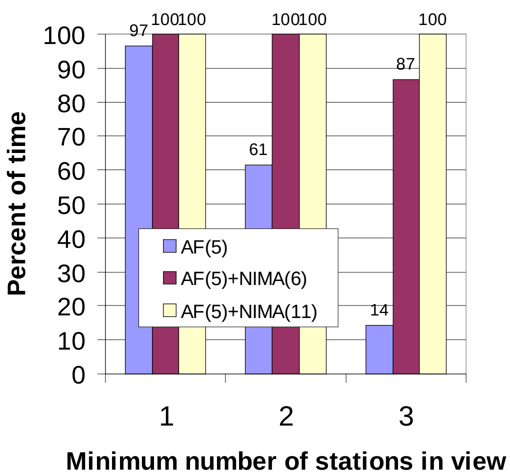

Figure 3. Ground Network Visibility, 5 deg elevation mask

PERFORMANCE ANALYSIS

Performance analysis determined the sensitivity of filter and broadcast error as a function of the number of NIMA monitor stations included in the network. The analysis was based on two weeks of real USAF and NIMA tracking data from August 1-15, 2002. The two-week interval was a trade-off between computer run-time and adequately representing actual system performance. The data interval was selected to avoid orbit adjusts (about once each year for each satellite). The constellation consisted of 22 Block II/IIA satellites and six Block IIR satellites during the study period. The analysis included three major steps (Figure 4): tracking data preprocessing, filter emulation using TRACE, and post-processing of the filter output to assess filter and broadcast performance.

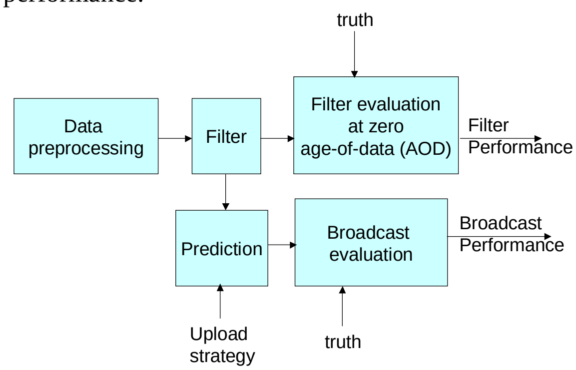

Figure 4. Performance Analysis Procedure

The NIMA tracking data files provided all available pseudo-range (PR) and accumulated delta-range (ADR) data for NIMA and Air Force stations. The PR data is 15-minute smoothed measurement data, time-tagged at the satellite. The ADR data is not currently used by the Operational Control Segment (OCS) and was not used in this study. Tracking data preprocessing included measurement editing based on range residuals and elimination of monitor station clock phase and frequency discontinuities.

The TRACE program was configured to emulate the OCS Kalman filter. Inputs included the measurement file, weather data, initial conditions for monitor station clocks, satellite clocks, and ephemeris, earth orientation parameter (EOP) data, and antenna phase centers. EOPs are included in the transformation from inertial to earth-fixed coordinates. The X and Y components reflect tilts (small angle rotations) of the geographic pole to the Earth's spin axis. The rotation about Z (UT1-UTC) is due to the fact that earth rotation rate is not constant. EOP data was available from two sources: (1) NIMA EOPs which are predicted weekly for use by the OCS, and (2) International GPS Service (IGS)/International Earth Rotation Service (IERS) final EOP bulletins [4] that contain smoothed, post-processed data. Antenna phase centers (lever arms) are the same for all Block II/IIA satellites. Block IIR satellite phase centers vary between satellites with negligible X and Y components. TRACE produced 15-minute emulated filter states for use in post-processing performance analysis.

Post-processing analyses included assessment of filter performance, broadcast performance, and navigation message update capability. Filter performance assessment used the TRACE filter output and NIMA truth (precise ephemeris and clock) to assess anticipated OCS filter (zero age-of-data) performance. Filter URE [5] was computed from radial (R), clock (C), in-track (IT), and cross-track (CT) errors by the equation:

$$URE = \sqrt{(\Delta R - \Delta C)^2 + 0.0192 * (\Delta IT^2 + \Delta CT^2)}$$

GPS broadcast performance was assessed using the TRACE filter output, NIMA truth, and TRACE reference trajectories and transition matrices. Inputs included the number of scheduled uploads per day (from one to three), contingency upload threshold (ranging between 2 and 5 meters), typical latency (estimation to broadcast) of 0.5 hour, and a constraint that inhibits a scheduled upload if it is scheduled to occur within one hour of a contingency upload. Contingency uploads are initiated by the operator when the estimated range deviation (ERD, or broadcast message minus filter state in the ranging domain) exceeds a specified threshold. Measures of predicted performance include broadcast URE and ERD. Improvements to WAGE [6] (the Wide Area GPS Enhancement technique that reduces age-of-data for military users by broadcasting radial minus clock corrections in the spare bits of subframe 4 of the navigation message) were also evaluated.

GPS performance was also evaluated by studying the impact of navigation message update (NMU) [7] as a function of satellite update interval. NMU, if fully implemented, will significantly reduce age-of-data to all users by disseminating clock and ephemeris corrections on the satellite crosslinks to correct the broadcast navigation message.

All analyses in this study assumed average weather data at each station for tropospheric modeling. A single partition Kalman filter was implemented reflecting the AII filter rather than the multi-partition filter currently used at the MCS. Measurement error standard deviations of 0.5 meter were assumed for all stations except at Colorado Springs where 1.0 meter was used to account for increased multipath. The Colorado Springs monitor station clock was used as a master clock. All other monitor station clocks had equal state noise covariances (Q). All satellite clocks had equal Qs. All uploads included 0.5-hour latency to account for the 15-minute Kalman filter update cycle and latency at the ground antennas (GAs). We assumed GAs were always available when needed for scheduled and contingency uploads. No navigation message fit or quantization errors were included.

PERFORMANCE RESULTS

Performance statistics include zero age-of-data (AOD) or filter URE, broadcast URE, WAGE URE, and ERD. Statistics were accumulated beginning two days into the simulation runs. Assuming 28 satellites, one scheduled upload per day with a contingency upload threshold of three meters, and NIMA EOP data, filter error (zero age-of-data) is reduced from 0.74 to 0.47 meter (36%) using the six core NIMA stations, and to 0.39 meters (reduced by 17% more) with the five additional NIMA stations (Figure 5). Broadcast URE is reduced by about 10% using the core stations and an additional 3% with five more stations. Broadcast URE improvement is small because error is dominated by satellite clock prediction error. WAGE error reduction is similar to broadcast URE. Simulated ERD statistics for the five-station Air Force only configuration are in reasonably good agreement with actual estimates from August 2002 [8] OCS data (Figure 6), validating the simulation results. In particular, the five-station simulated ERD is 1.29 meters (Figure 5) compared to 1.35 meters (far-right purple column in Figure 6) for actual OCS performance. The analysis generated a few more satellite uploads per day than is currently performed (average of 44 versus 37). Reducing the number of contingency uploads would be expected to increase the ERDs. The differences between simulation and the OCS can be attributed to different filter Qs, GA scheduling constraints, filter partitions in the real system, and differences in upload latencies.

Elimination of four poor-performing satellites (two satellites with poor clocks, two satellites with large ephemeris errors due to momentum dumping) resulted in an overall 10% reduction in error (filter, broadcast URE, and WAGE) (Figure 7) compared to the full 28-satellite constellation. Filter error (zero AOD) is reduced by 17% using the five additional NIMA stations, but the impact on broadcast error is small (under 3%). All subsequent results presented in this paper are based on this 24-satellite constellation.

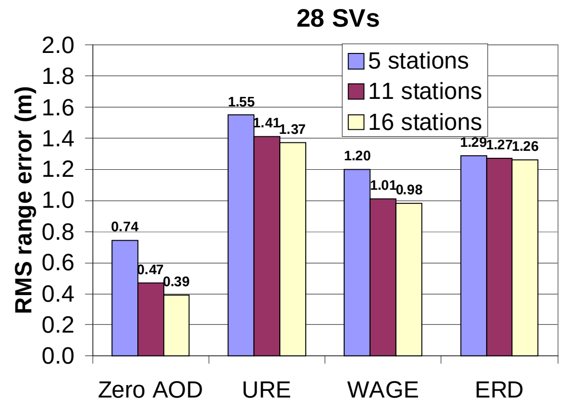

Figure 5. Performance Sensitivity to Number of Stations with 28 Satellites

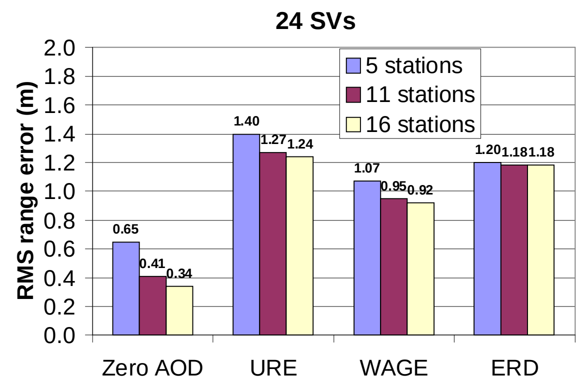

Figure 7. Performance Sensitivity to Number of Stations with 24 Satellites

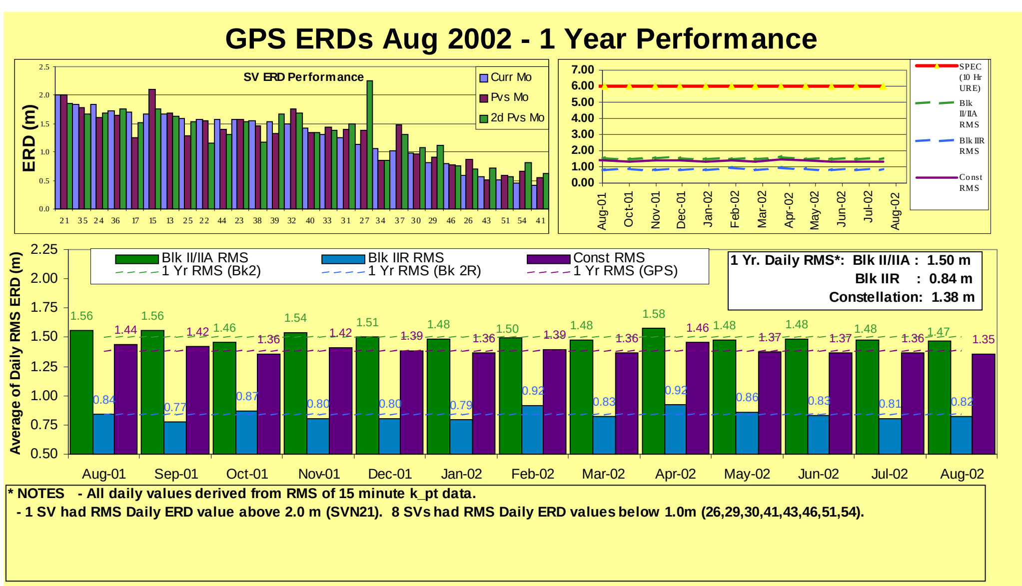

Figure 6. OCS Performance Data

IMPACT OF EOP DATA

NIMA predicts EOP data weekly for use by the OCS. NIMA implemented EOP data improvements starting in September 2002 (after the data interval in this study) that integrated improved prediction methods [9]. A second modification, planned for September 2003, is to restore the zonal tides to the model. The International Earth Rotation System/International GPS System (IERS/IGS) EOP data solutions are smoothed, post-fit quantities, with final values published monthly, 30-60 days after-the-fact, and are considered truth.

Figure 8 compares the various NIMA EOP predictions to the smoothed values of the IERS/IGS EOP data for the month of August 2002. Units are converted to meters for the terrestrial user. Modification to the NIMA EOPs primarily improves the Z rotation (UT1-UTC), making all three error components have the same order of magnitude.

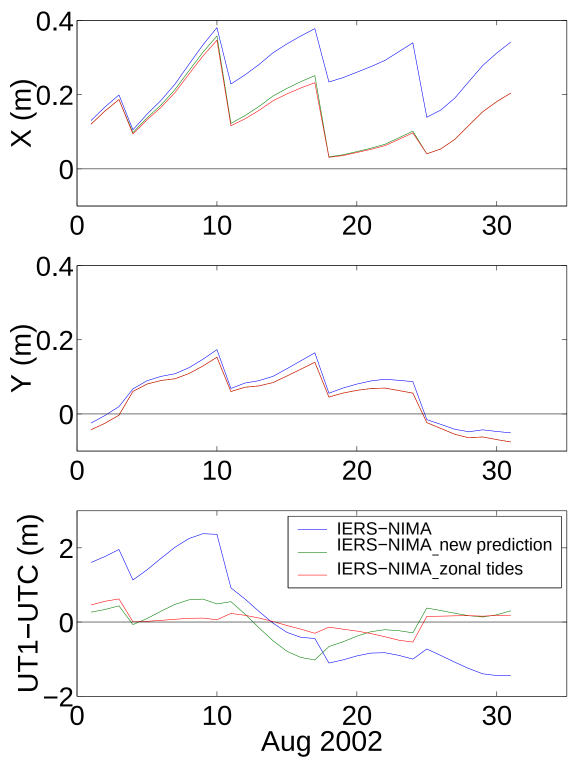

Figure 8. Difference in EOP Between IERS and Various NIMA Models

The improvement of the NIMA EOP model drives the filter performance (Figure 9) toward those results achieved using the IERS/IGS "truth" post-fit model. Incorporation of EOP estimation in the OCS Kalman filter could push system performance even closer towards the performance achieved with the IERS/IGS model.

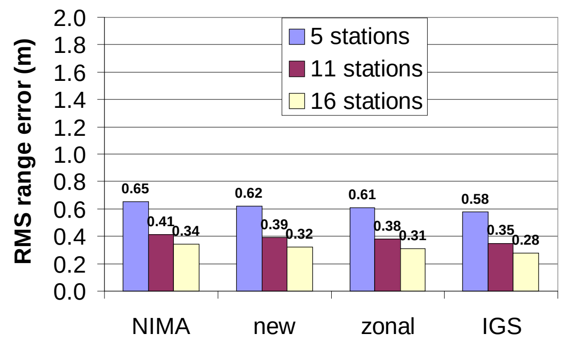

Figure 9. Filter URE Performance Sensitivity to EOP Data: Three NIMA cases and IGS Finals

IMPACT OF SATELLITE CLOCK PERFORMANCE

Performance analysis using only good Rubidium clocks (5 IIR and 3 IIA satellites) confirms the substantial benefit of improved satellite clocks (Figure 10) [10,11]. All other parameters are baseline values (August 2002 NIMA pole data, one upload/day, 3-meter contingency threshold). Filter performance improves by about 20% (e.g., from 0.65 to 0.51 meter for five stations) using Rubidium clocks only. Broadcast URE performance improves by about 35-40% due to better clocks (e.g., from 1.40 to 0.91 meter with just five stations) because clock prediction error is substantially reduced. It is anticipated that a full constellation of highly stable Rubidium clocks will show similar benefits.

The six NIMA core stations improve zero AOD performance by 33% (0.51 to 0.34 meter) and broadcast URE by 16% (0.91 to 0.76 meter). The additional five NIMA stations improve zero AOD performance by 20% (0.34 to 0.27 meter) but have minimal impact on broadcast performance (0.76 to 0.74 meter) because the age-of-data is large and, in this case, ephemeris errors dominate the URE.

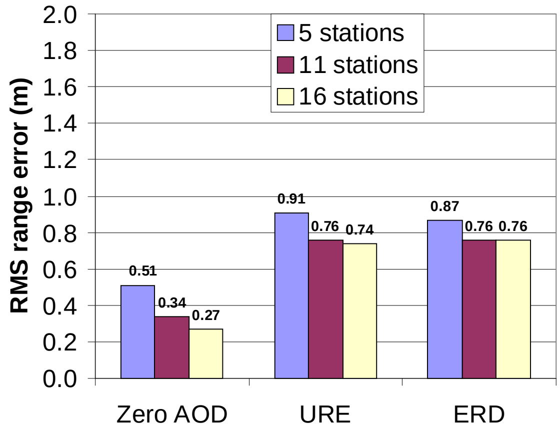

Figure 10. Rubidium Clock Performance

REDUCED AGE-OF-DATA

Increasing the number of scheduled uploads per day improves performance (Figure 11) at the expense of increased operator workload and MCS processing. For example, increasing the number of scheduled uploads from one to two per day for each satellite improves broadcast URE performance by 10-15%. Similar improvements are achieved in ERD and WAGE performance (not shown). The impact of the additional five NIMA stations remains small because the error is still dominated by navigation message age-of-data (six-hour average age-of-data for two uploads per day).

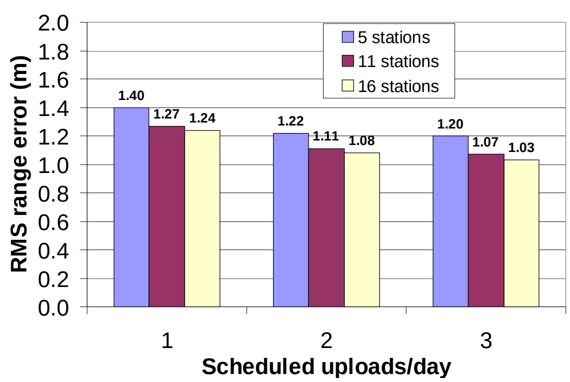

Figure 11. Broadcast URE Sensitivity to Number of Scheduled Uploads

Reducing the contingency upload threshold improves performance at the cost of increasing the number of uploads per day. About 15% accuracy improvement is achieved by reducing the contingency upload threshold from 3 to 2 meters, but the average number of daily uploads increases from 39 to 52 (more than 30% increase in number of uploads).

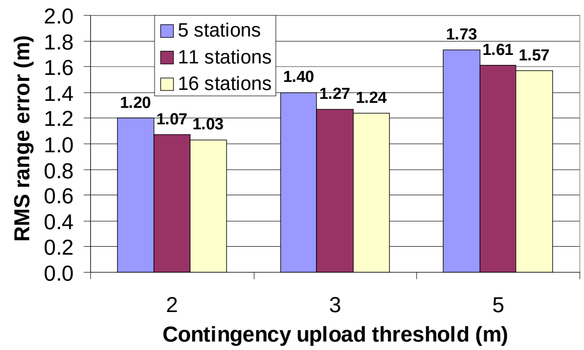

Figure 12. Broadcast URE Sensitivity to Contingency Upload Threshold

Navigation Message Update (NMU), if implemented, will significantly reduce age-of-data to all users by disseminating clock and ephemeris corrections on the satellite crosslinks to correct the broadcast navigation message. The NMU assessment program uses the same inputs as broadcast performance evaluation, plus an input that defines the satellite update interval ranging from 0.25 hour to 3 hours. NMU is the most effective broadcast accuracy enhancer because it reduces age-of-data with the fewest satellite contacts.

NMU with a 0.50-hour update interval can reduce broadcast URE to 0.70 meter (50%) from 1.40 meters (Figure 13) even with the existing satellite clock constellation and five-station ground system. The core NIMA stations, with the same NMU implementation, improve SIS performance by about 30%. The additional five NIMA stations improve performance by another 10-15%, demonstrating the potential of these NIMA stations under low age-of-data conditions.

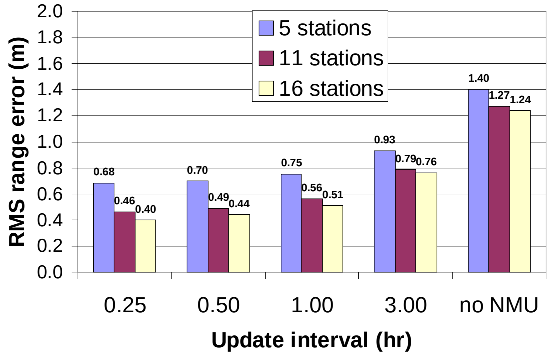

Figure 13. Broadcast URE with Navigation Message Update

CONCLUSIONS

Five additional NIMA stations produce almost 20% improvement in filter performance. The impact on current broadcast URE performance is small, but the benefit of the five additional stations will increase to 10-15%, approaching the filter improvement, if low age-of-data NMU is implemented. The additional stations increase coverage from continuous dual-station to triple-station monitoring of all satellites, which is critical for timely, robust integrity monitoring. These significant improvements can be achieved at relatively small cost because the AII/AEP software already includes the capability to process data from 20 stations. The primary upgrade required is the installation and maintenance of dedicated communication lines from the additional NIMA sites to the St. Louis NIMA facility. Additional GPS performance improvements are expected as a result of improved earth orientation parameters, better satellite clocks, and reduced age-of-data achieved through more frequent scheduled uploads, reduced contingency upload threshold, and possible implementation of the navigation message update capability.

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